Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

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PREPARATION AND DOCUMENTATION OF A CATHENA INPUT FILE FOR DARLINGTON NGS

by

Atomic Energy of Canada Limited
Whiteshell Nuclear Research Establishment
Pinawa, Manitoba

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Preparation and documentation of a CATHENA input file for Darlington NGS

Prepared by Atomic Energy of Canada Limited

ABSTRACT

A CATHENA input model has been developed and documented for the heat transport system of the Darlington Nuclear Generating Station. CATHENA, an advanced two-fluid thermalhydraulic computer code, has been designed for analysis of postulated loss-of-coolant accidents (LOCA) and upset conditions in the CANDU® system. This report describes the Darlington input model (or idealization), and gives representative results for a simulation of a small break at an inlet header.

RÉSUMÉ

Un modèle d'entrée pour CATHENA a été mis au point et documenté pour le système de caloportage de la centrale électronucléaire de Darlington. CATHENA, un code machine avancé thermohydraulique pour deux fluides, a été conçu pour analyser les accidents postulés de perte de caloporteur et les conditions inhabituelles postulées de la filière CANDU®. Le présent rapport décrit le modèle d'entrée (c'est-à-dire son idéalisation) de Darlington et donne des résultats représentatifs pour la simulation d'une petite fracture d'un collecteur d'entrée.

DISCLAIMER

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EXECUTIVE SUMMARY

The purpose of this work, performed for the Atomic Energy Control Board (AECB), is to create and document a CATHENA idealization for the Darlington Nuclear Generating Station (NGS).

CATHENA, created at AECL, is an advanced, one-dimensional thermalhydraulic computer code developed primarily to analyze postulated loss-of-coolant-accident (LOCA) scenarios and upset conditions in CANDU® nuclear reactors. The code uses a non-equilibrium, two-fluid thermalhydraulic model to describe fluid flow. Component models describing the behaviour of pumps, valves, steam separators and discharge through breaks are included, to complete the idealizations of reactor systems. CATHENA is also able to model the complex control systems found in nuclear reactors.

CATHENA has been validated using a large number of experimental tests designed to investigate the thermalhydraulic behaviour of the CANDU heat transport system under upset and accident conditions. Good agreement with experimental results has been shown, increasing confidence in the ability of the code to predict thermalhydraulic phenomena and events in CANDU systems under LOCA situations.

The present input file, installed on the AECB VAX computer, will enable AECB staff to perform simulations of postulated events in the Darlington NGS. Because CATHENA is a two-fluid thermalhydraulic code, non-equilibrium effects expected during most postulated LOCA scenarios will be represented correctly. It should be noted that almost all CANDU thermalhydraulic safety analyses, performed to date, have been done with homogeneous codes.

This report describes the CATHENA Darlington NGS input file and presents a sample simulation performed with the model. Only a general description is given here because of proprietary information on plant design. However, a more detailed description has been presented in an AECL/AECB proprietary report, which is deposited in AECB file 34-2-152-2.

A. INTRODUCTION

1. Background

Part of the Atomic Energy Control Board's (AECB) mandate is to reviev reactor licensing submissions, and assess the validity of analyses that have been performed therein. Normally, a thermalhydraulic analysis of the sequence of events during postulated loss-of-coolant accidents (LOCA) or other upset scenarios forms part of the licensing submission. This will be the case with the Darlington Nuclear Generating Station (NGS).

It is important that AECB staff have access to advanced analytical "tools" with which they can check the thermalhydraulic analysis in licensing submissions. The CATHENA code offers this capability.

CATHENA[1] has been validated under a wide range of conditions and thus confidence may be placed on predictions made. Also, because of the flexible input arrangement used by CATHENA, sensitivity studies can easily be performed.

Almost all licensing calculations, performed to date, have used homogeneous thermalhydraulic codes (e.g., FIREBIRD[2], SOPHT[3]). CATHENA, a full two-fluid code, has the ability to check under which conditions a "homogeneous" assumption is valid, and under which conditions it "breaks down". This is particularly important in the study of Emergency Core Coolant (ECC) performance when "separated" flow is expected to occur in the reactor primary circuit.

It should be noted that the international trend is towards thermalhydraulic analysis using two-fluid codes (RELAP[4], TRAC[5], CATHARE[6], etc.). Also, Ontario Hydro is currently developing the two-fluid code, TUF.

2. Purpose of CATHENA Darlington NGS Input File

The CATHENA input file representing the Darlington NGS can be used by AECB personnel to perform analyses of postulated LOCA and upset scenarios for the plant. Also, existing analysis for the plant performed with other codes can be checked using the CATHENA model. These simulations may be performed on the AECB VAX or APOLLO computers, thus eliminating expensive costs from computer "service" bureaus.

3. Scope of Contract

The CATHENA input file, describing the Darlington NGS, is to be delivered and documented under the terms of this contract. The input model, as well as an up-to-date version of CATHENA, will be installed on the AECB VAX computer.

4. Contract Identification

This work was produced by AECL under contract to the Atomic Energy Control Board (AECB); AECB project number 2.152.2.

B. CATHENA CODE

1. Numerics

CATHENA is an advanced, one-dimensional thermalhydraulic computer code developed primarily to analyze postulated loss-of-coolant-accident (LOCA) scenarios and upset conditions in CANDU® nuclear reactors. The code uses a non-equilibrium, two-fluid thermalhydraulic model to describe fluid flow. Provision is also made for modelling a non-condensible gas in the vapour phase. Conservation equations for mass, momentum and energy are solved for each phase (liquid and vapour), resulting in a 6-equation model (7 if a non-condensible is present). Interphase transfer of mass, momentum and energy is calculated using a set of flow-regime-dependent constitutive relations. As well, flow-regime-dependent constitutive relations for wall shear specify momentum transfer between the fluid and the pipe surfaces.

The numerical solution method used is a staggered-mesh, semi-implicit, finite-difference method that is not transit-time-limited[7]. Conservation of mass is achieved using a truncation error correction technique similar to that used in RELAP5/MOD2[4].

Heat transfer from metal surfaces is handled by a comprehensive wall heat transfer package. A set of flow-regime-dependent constitutive relations specifies energy transfer between the fluid and the pipe wall and/or fuel element surfaces. Heat transfer by conduction within the piping and fuel is modelled in the radial direction and can be modelled in the circumferential direction as well. Radiative heat transfer and the zirconium-steam reaction can also be included. Built into this package is the ability to calculate heat transfer from individual groups of pins in a fuel bundle subjected to stratified flow. Under these conditions, the top pins in a bundle are exposed to steam while the bottom pins are exposed to liquid.

Component models describing the behaviour of pumps, valves, steam separators and discharge through breaks are incorporated in the code, to complete the idealizations of reactor systems. A more complete description of the CATHENA code is available in reference 1.

Control systems in CANDU reactors (e.g., boiler level/pressure control) can be quite complex. They are modelled in many other thermalhydraulic codes, such as SOPHT and FIREBIRD, as specialized FORTRAN routines. In CATHENA, a generalized system has been developed in which control systems are described by user-supplied input data[8]. Thus, sensitivity studies may be easily performed in the complex reactor control systems (e.g. "trip" set points).

One of the primary goals in the CATHENA development program is to maintain a generalized "user-friendly" input approach, in which the user models a reactor or test facility using only input data. Thus, only one version of the code is required.

CATHENA was developed by Atomic Energy of Canada Limited (AECL) at the Whiteshell Nuclear Research Establishment (WNRE) using a VAX 8650 computer system. It consists of over 80 000 lines of FORTRAN executable statements (about 700 subroutines).

2. Validation

The CATHENA code has been extensively validated using experimental data from the RD-12 and RD-14 thermalhydraulic loops[9,10], the Cold Water Injection Test (CWIT) Facility[11], and other experimental facilities. As well, the code has simulated a number of LOCA and upset conditions that occurred in actual CANDU plants[12]. The CATHENA calculations showed excellent agreement with plant data.

3. Host Computers

CATHENA was developed on a Digital Equipment Corporation (DEC) VAX 8650 computer using the VMS operating system. However, the code is written in "standard" FORTRAN-77 and has been installed on the APOLLO, CDC, and FPS computers.

Currently, a trend is seen in which large codes (such as CATHENA) are being installed on small super microcomputers with virtual memory systems such as the micro-VAX and APOLLO systems. These computers can be purchased for about $20k. Although the computing speed of these computers may only be less than 10% of a large mainframe computer, an "overnight or weekend run" can be sufficient to complete a complex simulation. Thus, it may be more economical to purchase a super microcomputer rather than purchase computer resources from a vendor. This has been reported in reference 12, prepared by the AECB.

C. DARLINGTON NGS IDEALIZATION

1. Introduction

The CATHENA idealization of the Darlington NGS heat transport system was generated using information supplied by the AECB. Because data used for this idealization are proprietary, specific details are not given in this report.

The description of the idealization is divided into three sections:

1) primary side,
2) secondary side, and
3) emergency core coolant system (ECCS).

A listing of the CATHENA input file for the Darlington NGS is given in the AECB-AECL proprietary report deposited in AECB File 34-2-152-2. The complete CATHENA idealization requires 327 nodes, and 361 links. A total of 2111 heat transfer surfaces are also modelled.

1.1 Primary Side

Figure 1 shows the CATHENA idealization of the primary heat transport system (PHTS) of the Darlington NGS. Components such as feeders, end fittings, pumps, etc., are labeled to define the CATHENA input specification. Each "box" in Figure 1 represents a node; components may have one or more nodes. The circles in the figure are used to designate boundary conditions with either flow, or thermalhydraulic conditions at a node. Solid lines show the connections between components, and arrows indicate the direction of flow. For example, "NE_COREA" represents the north-east average core, and is represented by 5 nodes.

The two primary circuits or loops are modelled. The 120 inlet feeders, 120 channels, and 120 outlet feeders connected between the inlet and outlet headers, in each of three passes through the reactor core, are combined into single representative inlet feeder, channel and outlet feeder, for each core pass. For the fourth North-East pass, one "hot" channel is modelled in parallel with an average representation of the remaining 119 channels. This arrangement is used to investigate the behaviour of a high power channel under LOCA conditions. The four pumps and four steam generators, required to complete the PHT circuit are also shown in Figure 1. Figure 2 shows the pressurizer as well as the feed and bleed circuits, including interconnecting piping. Note that these circuits are connected to NE and SE outlet headers and the SW and NW pump suctions.

Heat transfer models, which represent pipe walls, have been incorporated in CATHENA. They model heat transfer from the primary fluid to the pipe walls and, in the case of the steam generator tubes, from the pipe walls to the secondary side. The primary piping was assumed to be adiabatic, i.e, no heat loss to the environment. The metal mass and heat transfer areas in contact with the primary fluid were made as accurate as possible. For complicated geometries (i.e., headers) the heat transfer area is not simply a product of the pipe diameter and length, but includes other metal mass (i.e., header ends, stubs) as well. Since the inside and outside diameters of the wall models are derived from the heat transfer areas and metal mass, they may differ from those of the actual pipe.

Control systems for PHTS inventory (feed and bleed), reactor trip logic, and ECCS have all been modelled.

1.2 Secondary Side

The secondary side was modelled from the steam generator inlet up to the outlet of the steam headers for both figure-of-eight halves of the reactor. The secondary side was modelled with sufficient detail to capture the effect of secondary side performance on the PHTS under LOCA conditions.

The behaviour of the feedwater flows, reheater flows, main steam line safety valves and the steam turbines were simulated by applying CATHENA's System Control Models to each of the pressure/flow boundary conditions. Thus the behaviour of the plant control systems was built into the System Control Models by means of the input data. No special user subroutines were required.

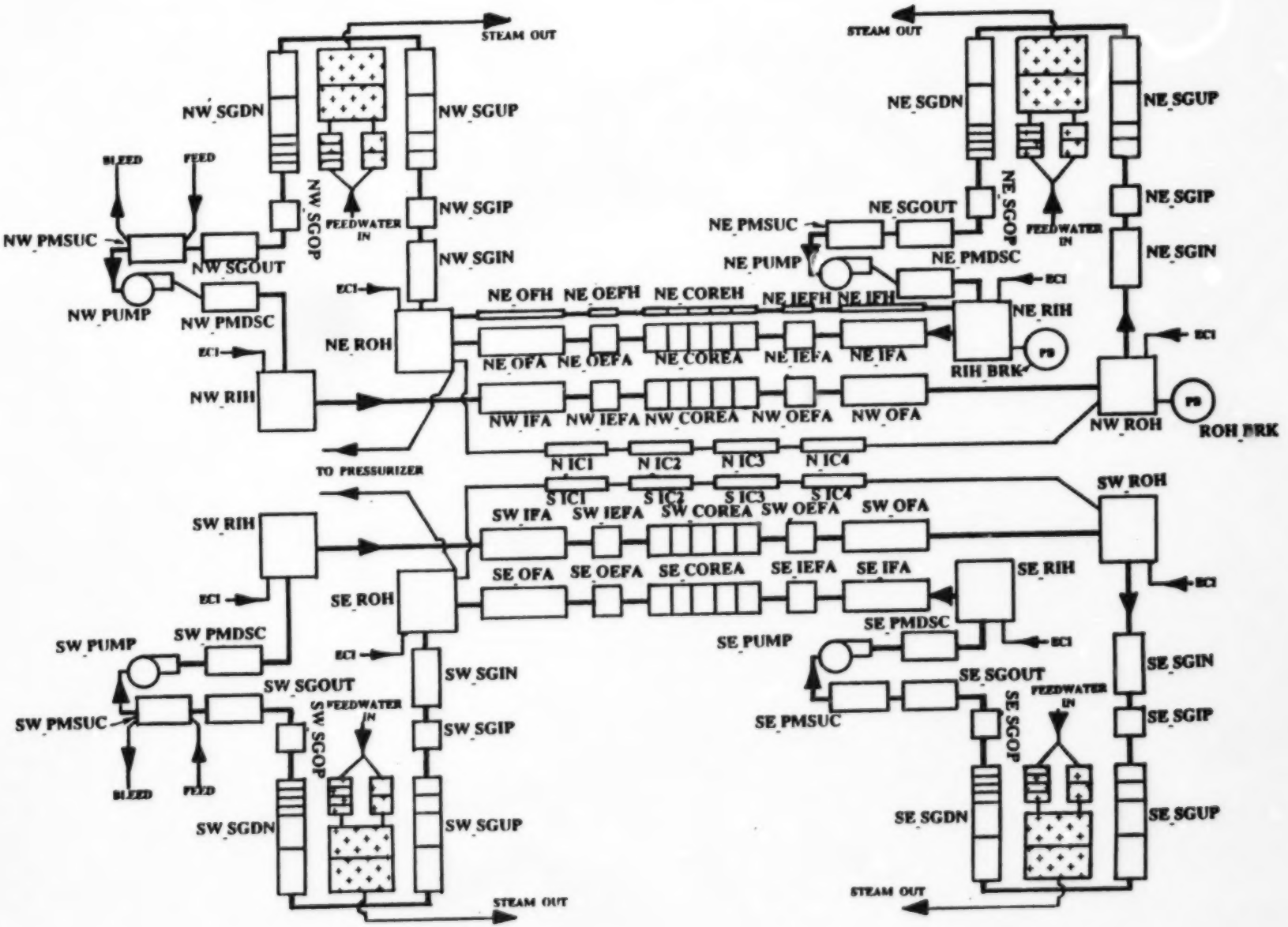

FIGURE 1: Primary Heat Transport System

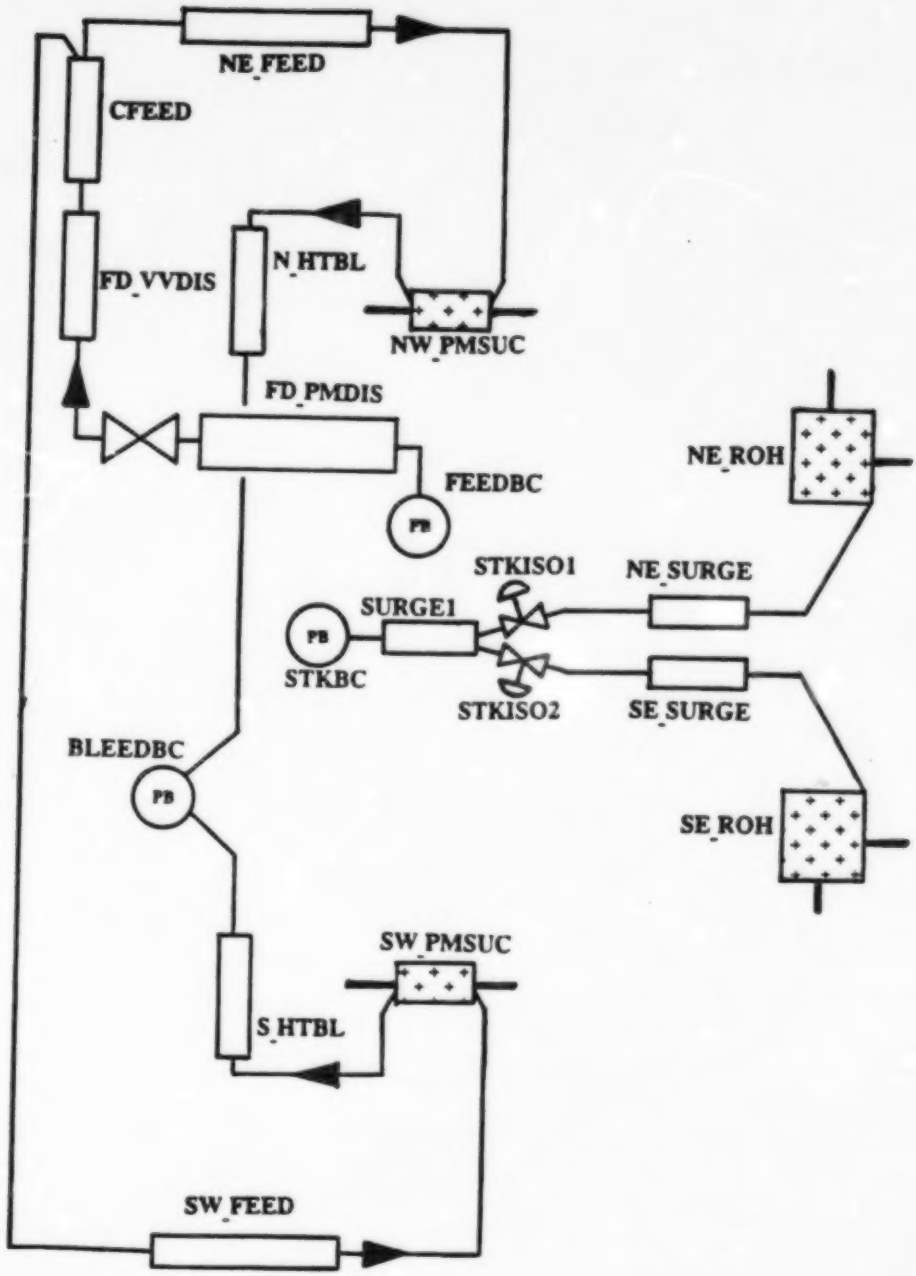

FIGURE 2: Inventory Control

Figure 3 gives the nodalization for the CATHENA representation of the Darlington NGS secondary side. The idealization starts at the feed water deaerator and stops at the steam turbine. A 12-node boiler representation is used, which is capable of accurately modelling recirculation in the steam generator under LOCA and upset conditions.

The CATHENA idealization includes the four steam generators, the feedvater lines and control valves for each steam generator, and the steam lines from each steam generator to the steam turbine balance header. The steam by-pass to the reheater vas also included. The safety relief valves (SRV) and atmospheric steam discharge valves (ASDV) are modelled for each steam generator.

Wall heat transfer models for the secondary side circuit include the heat transfer between the primary and secondary circuits through the tube bundle as well as the wall thermal mass of the steam generators. Stored heat in the metal mass is important during transients when steam generator "crash cooldown" is initiated, or when a main steam-line break is postulated.

CATHENA "system control" models are used to represent the boiler level control (BLC) and boiler pressure control (BPC) of Darlington NGS. This is done by controlling feed vater flov and steam flov to the turbine. Logic is also modelled to control the opening of the SRVs and the ASDVs.

1.3 Emergency Core Coolant System (ECCS)

The CATHENA idealization of the ECCS is shovn in Figure 4. Both the medium- and high-pressure nodes are modelled from the storage tank to the eight headers. The opening of the isolation valves is controlled by logic specified "system control" models.

D. CATHENA RESULTS

1. Steady-State

When the CATHENA idealization of the Darlington NGS vas complete, a steady-state simulation was performed. This calculation predicts the normal operating conditions of the plant. CATHENA results shov that pressures in the PHT system and the secondary side are matched within ±2% of design conditions, and the predicted flov is within ±4% of the design flov in the reactor.

2. A Transient Simulation

A transient calculation was also performed to ensure that reactor control systems modelled by CATHENA vere operating correctly. The case chosen vas a postulated small break at an inlet header. Figure 5 shovs a sample result for this postulated LOCA scenario. This simulation demonstrated that the reactor trip, controlled steam generator cooldovn, and ECI injection occurred according to Darlington NGS design specifications.

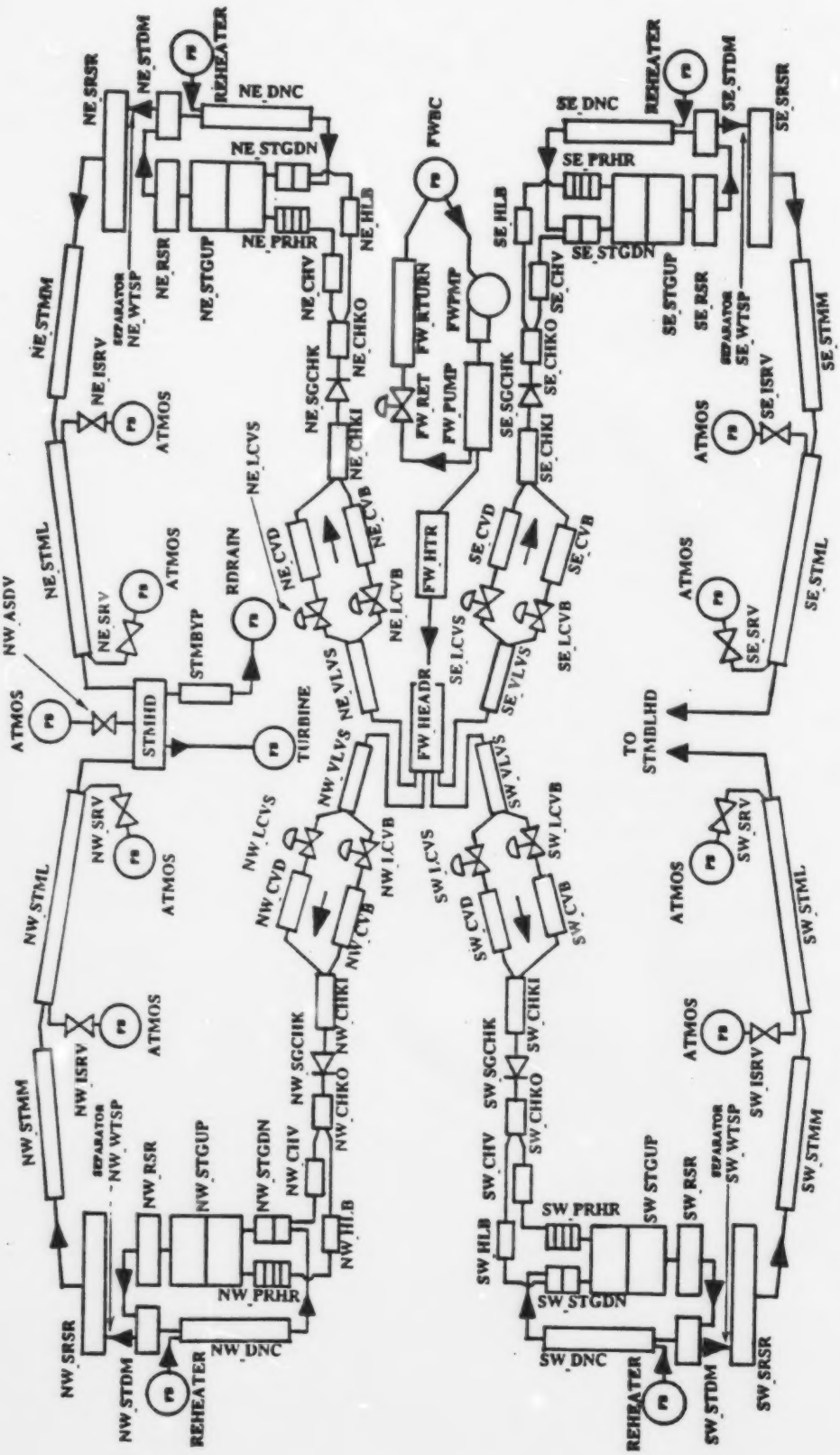

FIGURE 3: Secondary Side

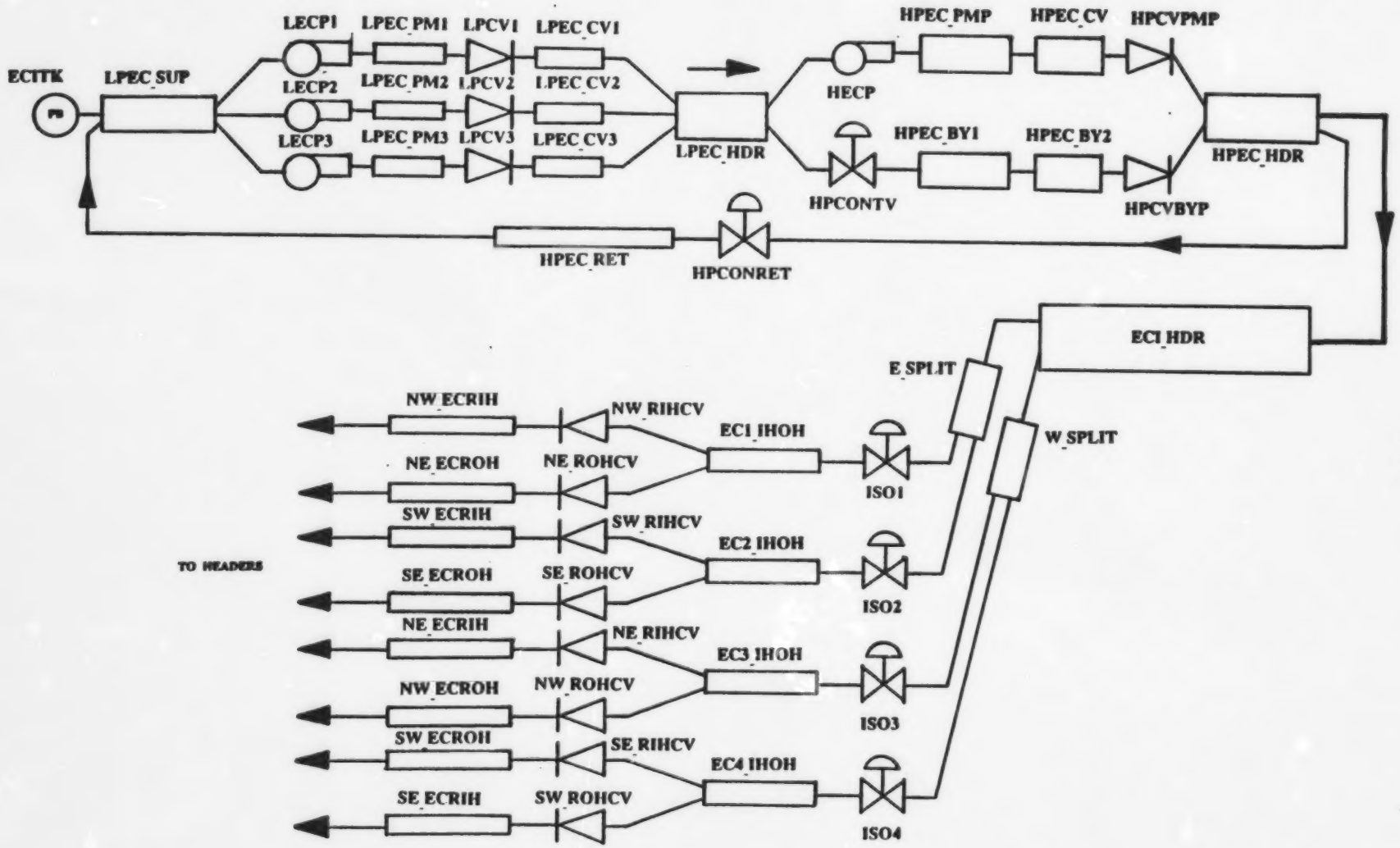

FIGURE 4: Emergency Core Coolant System

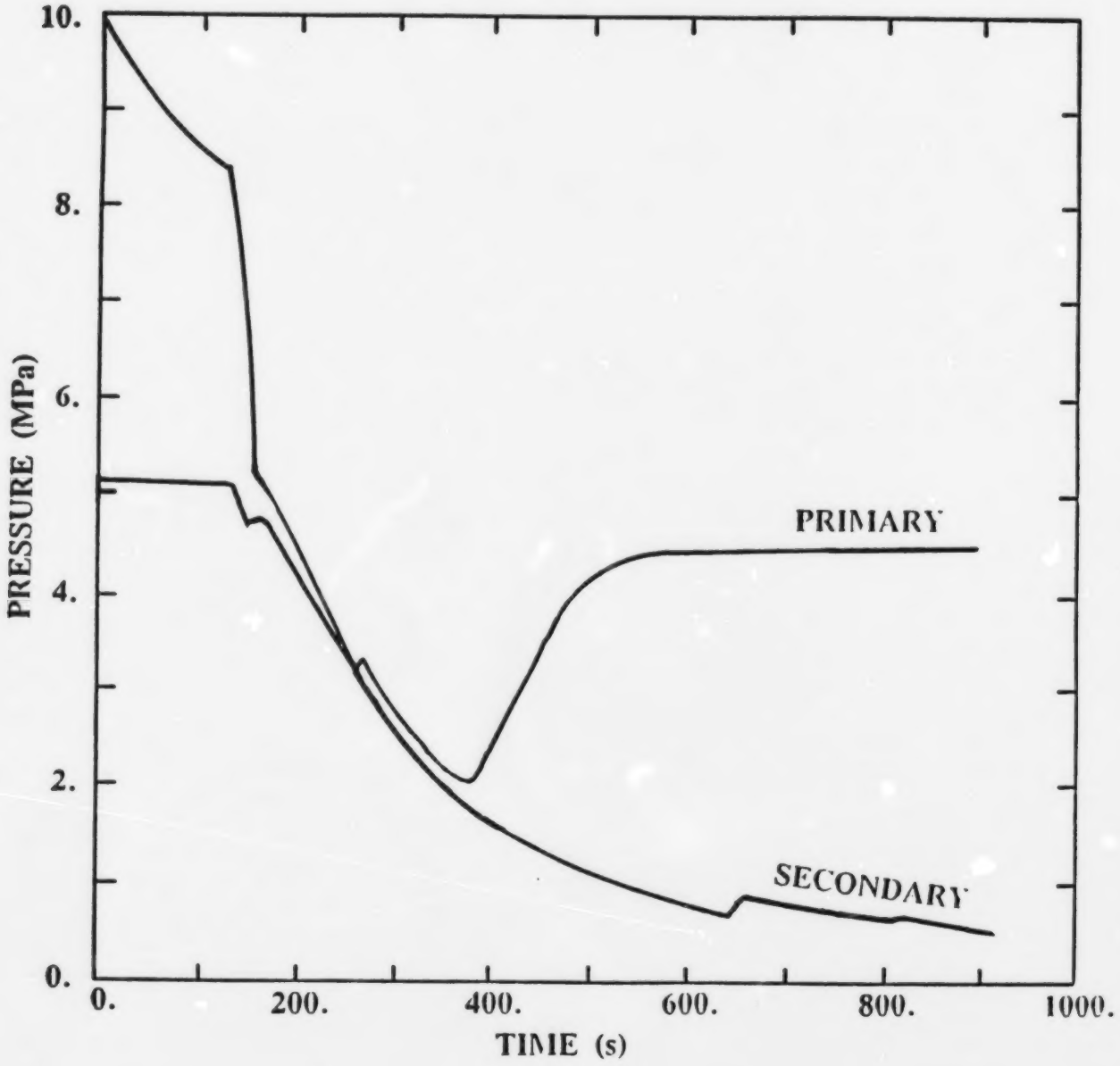

FIGURE 5: CATHENA Predictions of Primary and Secondary Pressure for a Small Break at an Inlet Header

E. CONCLUSIONS

The completion of this project within the short time span of three months has demonstrated the ease with which CATHENA can be used in modelling different reactor systems. Also, it has been shown that the modelling of the complex reactor control systems of Darlington NGS can be done with user-specified input. This allows sensitivity studies, examining the reactor control and safety systems (e.g., "trip" setpoints), to be performed easily by AECB staff.

The Darlington NGS input file has been installed on the AECB's VAX computer with the current up-to-date version of CATHENA. A sample simulation was performed on the AECB computer and compared to the same calculation on the WNRE computer on which CATHENA was developed. Results were the same, ensuring a correct transfer of the CATHENA code and the Darlington NGS input file to the AECB.

F. RECOMMENDATIONS

The CATHENA Darlington NGS input file should be used to check the thermalhydraulic safety analysis performed in the licensing submission for this plant. If differences between licensing submission and CATHENA results are observed, the reasons for the discrepancies should be identified and examined.

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